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Experimental Validation of a Photoemission Model for End-to-End Beam Simulations and Custom Photocathode Designs

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Abstract: *This paper outlines the experimental techniques used to validate a photoemission model applied to metals with sub-monolayer alkali coatings. Essential features of the model are highlighted and its results are compared to experiment. Cesium was deposited in-situ on tungsten and silver polycrystalline substrates while quantum efficiency (QE) was measured as a function of surface coverage and other parameters. Good qualitative agreement with theory is demonstrated and significant differences in quantitative comparisons are addressed.*

Keywords: QE, dispenser cathode, photoinjection

Introduction

Photoinjectors are important electron sources for free electron lasers (FEL's), energy-recovery linac (ERL) driven x-ray sources, high energy linear colliders, and other applications. Laser-switched photocathodes are used to prebunch electron beams for injection into rf linacs. All photoinjector concepts include a drive laser and photocathode to produce high beam current with low emittance [1]. For prompt emitters, the electron bunch pulse structure mimics that of the laser pulse. Ideally, photoemission delivers a high quality beam with extraordinary peak current and flexible pulse formats. Additionally, photocathodes are compatible with low-temperature (cryogenic) applications and, in the case of GaAs, are a source of spin-polarized electrons [2]. Their fabrication, however, is not routine. The surface layer of alkali or alkali earth metal(s) is crucial for emission to occur in the visible range. These layers are vulnerable to ion bombardment, contamination, and desorption and are damaged with use. It has been established that the degradation mechanism is loss of cesium from the surface or surface compounds. The solution we have advocated elsewhere is based on the dispenser cathode concept [3, 4]. In this configuration, cesium diffuses to the surface through porous channels to replace the damaged layer, potentially resulting in kilohours of operational lifetime. The development of a controlled porosity dispenser cathode, in addition to end-to-end modeling of photoinjector-based accelerator systems, requires a validated photoemission model that accounts for drive laser particulars (the needs of which are generally at odds with the needs of the photocathode) and photocathode material and configuration parameters. The experimental utility of this model is its predictive selection of optimal photocathode components and composition.

Photocathode Characteristics

Metrics of photocathode performance are quantum efficiency, robustness, and lifetime. Bare metal photocathodes (e.g., Copper) are rugged, prompt, and long-lived emitters but (for high power FEL's) place unrealistic demands on current laser technology as their low QE requires high power and short wavelengths. Conversely, higher QE cathodes operate at longer wavelengths and less power, but are generally short-lived, complex to build, and sensitive to the vacuum environment. QE can be improved through a judicious modification of the work function at the cathode surface, accomplished by adding a fractional monolayer coating of alkali-metal(s).

Photoemission Model

Quantum efficiency relates the number of electrons emitted to the number of photons absorbed, or $QE = (\Delta Q / e) / (\Delta E / \hbar \omega)$, where ΔQ is emitted charge and ΔE is incident energy. For photon energies in excess of the work function of a metal, the time constants and illumination area of the laser are the same as the time constants and emission area, so that current and laser intensity can replace emitted charge and absorbed energy, respectively, so that the quantum efficiency becomes

$$QE = \frac{\hbar \omega}{e} \left(\frac{J_e}{I_\lambda} \right) = 1.2398 \frac{J_e [\text{A/cm}^2]}{I_\lambda [\text{W/cm}^2] \lambda [\mu\text{m}]} \quad [1]$$

By taking into account thermal effects, reflectivity, and electron scattering phenomena, we have found that [5, 6]

$$J_e(\beta, F, \Phi) = \left(\frac{e}{\hbar \omega} \right) f_\lambda (1 - R) I_\lambda(t) \left\{ \frac{U[\beta(\hbar \omega - \phi)]}{U[\beta \mu]} \right\} \quad [2]$$

where $\beta = 1/k_B T_e$, T_e is the electron temperature, $R(\theta)$ is the angle- and material-dependent reflectivity as a function of wavelength, μ is the chemical potential and ϕ is the height of the barrier above the Fermi level (that is, the work function lowered by the Schottky factor for an image charge potential). $U(x)$ is an extension of the Fowler-Dubridge function. The time-dependent model contains material and laser-dependent features, dominated by the manner in which QE varies with cesium coverage, the photoemission probability, and the impact of electron scattering after photoexcitation. The work function Φ for partial coverage θ is found using Gyftopoulos-Levine theory. For our laboratory conditions, the model contains

virtually no adjustable parameters. Complications to the Experiment-theory comparison include: surface profilometry; reflectivity and work function dependence on exposed crystal face; high work function contaminants (e.g., Carbon) present at the surface; and conditions such that only sub-areas are contributing to emission.

Experimental Techniques

Cesium on Tungsten (Cs-W), despite its admittedly low QE, provides an ideal experimental test of the photoemission theory because its material properties and fabrication techniques are historically well-documented. Data was obtained by illuminating a plasma-cleaned sheet of poly-crystalline tungsten with highly stable CW diode lasers (<1% power fluctuation), while monitoring photocurrent using a picoammeter. Cs was deposited using commercially available sources, containing cesium chromate and titanium powders, and measured with a crystal balance. Under such conditions, θ is linearly related to the "depth" of Cs. Sources were activated through resistive heating and temperature was continuously adjusted through a feedback loop to maintain a constant deposition rate. The anode - cathode potential difference was 200V (separation distance of 0.5cm) and the entire anode-cathode-ammeter circuit was electrically isolated from the rest of the experiment to reduce noise. The base pressure of the UHV system was maintained at 3×10^{-10} Torr, reaching 2×10^{-9} Torr during the cesium deposition process because of slight outgassing. An RGA was used to check that the gasses released did not contain those detrimental to cathode performance, such as carbon monoxide and water vapor. Figure 1 shows theory (line) compared to experiment (points) for QE at several wavelengths. Figure 2 illustrates the same model under the same conditions, but for Cs on Ag: the agreement is within 15-20% (similar to the agreement obtained for bare metal QE data in the literature).

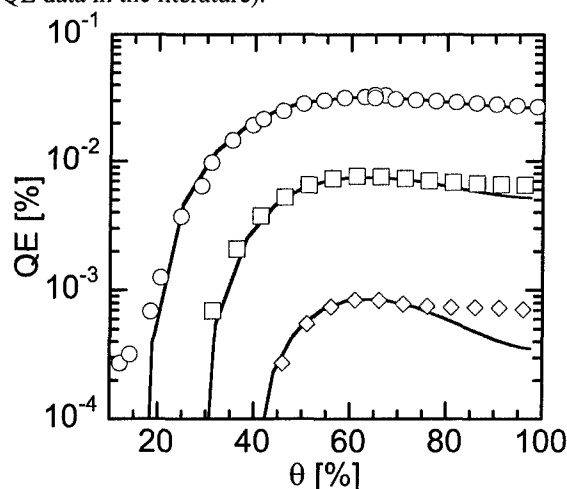


Figure 1. Theory (line) vs. experiment (marker) for Cs on W for 405 nm (circle), 532 nm (square), and 655 nm: theory has been scaled by 1.4, 1.4, and 0.85, respectively.

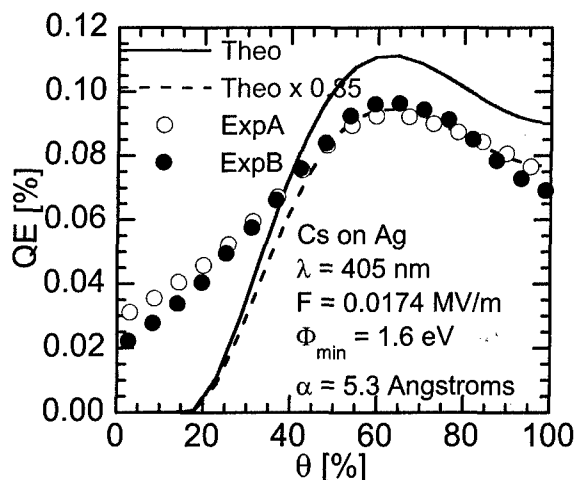


Figure 2. Same as Fig. 1, but for Cs on Ag: solid line is unscaled theory; dashed line is scaled by 0.85.

Conclusion and Future Work

The qualitative agreement in the case of Cs-Ag suggests that with further refinement, the model could predict cathode performance as a function of coating composition. The quantitative discrepancy is worse at low coverage ($\theta < 30\%$) because small amounts of residual cesium from previous experiments remained on the surface and could not be removed without excessive heating that causes the silver substrate to melt. In the future, an ion beam will be used to clean the cathode substrate at room temperature and other cathode compositions, such as CsKSb, will be explored for use with the dispenser concept. Changes to the photoemission model will include improved treatment of transmission probability across the workfunction barrier and an integrated model of transport plus emission. At present, barrier reflections are neglected and this becomes erroneous when the energy of photoexcitation approaches the barrier height.

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